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CATENA
Catena 73 (2008) 166–173
www.elsevier.com/locate/catena

Linking fragipans, perched water tables, and catchment-scale hydrological processes

P.A. McDaniel [a,*], M.P. Regan [b], E. Brooks [c], J. Boll [c], S. Barndt [d], A. Falen [a], S.K. Young [a], J.E. Hammel [a]

[a] *Soil and Land Resources Division, Box 2339, University of Idaho, Moscow, ID 83844-2339, United States*
[b] *USDA, NRCS, Portland, OR 97232, United States*
[c] *Biological and Agricultural Engineering Department, Box 442060, University of Idaho, Moscow, ID 83844-2060, United States*
[d] *Bonneville Power Administration, P.O. Box 3621, Portland, OR 97208-3621, United States*

Received 25 January 2007; received in revised form 14 April 2007; accepted 25 May 2007

Abstract

Soils with very slowly permeable fragipans and fragipan-like argillic horizons are extensive throughout the Palouse Region of northern Idaho and eastern Washington, USA. These soils develop seasonal perched water tables (PWTs) under the xeric moisture regime of the region. The objective of this study was to utilize a hydropedology approach to examine the linkages between fragipans, PWTs, and catchment-scale hydrological processes such as soil water storage, runoff, and lateral throughflow. A 1.7-ha catchment dominated by Fragixeralfs (Fragic Luvisols) was instrumented with 135 automated shallow wells to monitor PWTs. Soil water content was measured with water content reflectometry probes, and catchment outflow was measured with a flume. A 35 m × 18 m plot was isolated hydrologically from the surrounding hillslope using tile drains and plastic sheeting to measure perched water outflow. Results show that during the wet winter and spring months, the transition from unsaturated to saturated conditions is accompanied by changes in volumetric water storage of only 4–5%. PWT levels are at the surface of ~26–45% of the catchment soils during periods of high rainfall and snowmelt, thereby generating saturation-excess surface runoff from hillslopes. Observed solute movement via subsurface flow is very rapid and ranges between 2.9 and 18.7 m d^{-1} when PWTs are maintained in more-permeable Ap and Bw horizons. Subsurface lateral flow accounts for as much as 90% of the incident precipitation and snowmelt during early spring. Data indicate that the relatively shallow depth to the fragipans and high K_{sat} in surface soil layers combine to create a very flashy hydrological system characterized by considerable temporal and spatial variation in patterns of saturation-excess runoff.

Keywords: Fragipans; Hydrology; Perched water tables; Runoff; Subsurface flow

1. Introduction

Soils having perched water tables (PWTs) occupy ~82 million ha in the USA (unpublished Natural Resources Conservation Service STATSGO database). Regionally, PWTs are extensive in the Palouse region of northern Idaho and eastern Washington where they form above argillic horizons that also qualify as fragipans or have fragic characteristics with very low saturated hydraulic conductivity (McDaniel et al., 2001; Brooks et al., 2004). Under the region's xeric moisture regime, PWTs typically form in December and persist into May. Numerous studies have examined the temporal and spatial dynamics of PWTs at the hillslope scale (e.g. Palkovics et al., 1975; McDaniel and Falen, 1994; Cox and McFarlane, 1995; Calmon et al., 1998; McDaniel et al., 2001).

Relatively fewer studies have examined the linkages between fragipans, PWTs, and landscape-or catchment-scale hydrological processes such as water storage, runoff, and throughflow. Miller et al. (1971) estimated that roughly half of the January-to-June precipitation was accounted for as subsurface lateral flow above a fragipan in Ohio. They estimated that subsurface lateral drainage was >80% of the monthly precipitation during February. Water yield from a perched water system in Pennsylvania was found to

* Corresponding author.
E-mail address: pmcdaniel@uidaho.edu (P.A. McDaniel).

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doi:10.1016/j.catena.2007.05.011

correspond directly to streamflow during November (Palkovics and Petersen, 1977). Also in Pennsylvania, hillslopes with fragipan-containing soils produced considerably more runoff than did those without fragipans (Needelman et al., 2004). PWTs have been shown to develop more rapidly and persist longer in lower landscape positions (Hammermeister et al., 1982) and be responsible for rapid, lateral movement of solutes on hillslopes (Mallawatantri et al., 1996; Reuter et al., 1998).

Recent work by Needelman et al. (2004) has demonstrated the application of variable source area (VSA) hydrology to fragipan-containing soils. The term VSA hydrology was first used by Hewlett and Hibbert (1967) and is used to describe the spatially and temporally variable response of a watershed to precipitation (Ward, 1984). Processes such as runoff are driven by spatial and temporal variables within a landscape, including topography, geology, soils, climate, and management (Needelman et al., 2004). Because of their proximity to the soil surface, dense, slowly permeable fragipans are an important controlling factor in VSA hydrological processes in heterogeneous watersheds (Gburek et al., 2006).

Hydropedology has been suggested as an intertwined branch of soil science and hydrology that can be used to address interactive pedologic and hydrologic processes at a variety of scales (Lin, 2003). This approach integrates the pedon and landscape paradigms to link phenomena occurring at various scales (Wilding and Lin, 2006), and has been modified to include the shallow saturated zone (Gburek et al., 2006). Because hydrologic processes such as recharge, discharge, and interflow are controlled by soil and landscape attributes (Wilding and Lin, 2006), a hydropedological approach seems well suited to evaluate the influence of fragipan soils on these catchment-scale processes.

This approach has been applied to a temperate humid watershed in Pennsylvania, USA, where runoff generation was compared in two heterogeneous watersheds; 13% of one watershed was comprised of fragipan soils and the other watershed contained no fragipan soils (Gburek et al., 2006). Areas with fragipan soils were shown to generate saturation-excess runoff, whereas little or no runoff was generated in portions of the watersheds where fragipans were absent (Gburek et al., 2006). In this paper we also examine the linkages between fragipans, PWTs, and hydrologic processes, but within the context of a homogenous catchment comprised of one fragipan-containing soil series. Specifically, we link spatially explicit pedon-scale data to catchment water storage, surface runoff, and lateral subsurface flow.

2. Materials and methods

2.1. Site description

The study area consists of a small 1.7-ha catchment located approximately 3 km north of Troy, Idaho (Fig. 1). The catchment lies near the eastern margin of the 20,000-km^2 area of deep loessial soils in the northwestern USA known as the Palouse region (Busacca, 1989). Surface soils have formed in Holocene loess and typically include part of a late Pleistocene paleosol that is expressed as an argillic and fragipan (Btxb) horizon (Kemp et al., 1998). The study catchment was chosen

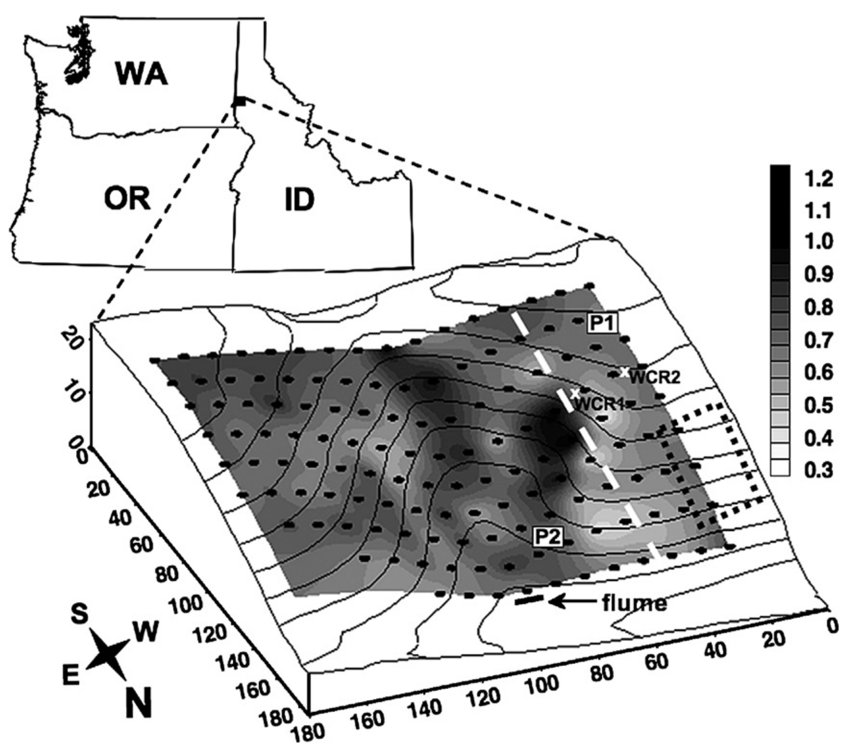

Fig. 1. Study site location (inset) and block diagram showing experimental design. Black circles indicate location of monitoring wells; shading pattern indicates depth to fragipan in meters. Block distances are in meters. WCR1 and WCR2 represent locations of soil water content probes; P1 and P2 represent locations of pedon sampling pits; dashed white line shows location of hydraulic conductivity sampling transect; black dotted rectangle (lower right side of block diagram) shows location of the hydrologically isolated hillslope plot.

because it is typical of the landforms commonly found in the region and the soils are mapped as predominantly one soil series. Soils at the site are mapped as a consociation of the Santa series, which are classified as coarse-silty, mixed, superactive, frigid Vitrandic Fragixeralfs (Barker 1981; Soil Survey Division, 2006) or Fragic Luvisols in the World Reference Base for Soil Resources (WRB) (FAO/ISRIC/ISSS, 1998). Two excavations with a minimum size of 1 m × 75 m × 1.25-m deep were used to collect bulk samples for standard characterization analyses.

The study area was cleared of forest vegetation in the 1960s for grain/legume production. Native tree species included grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), and ponderosa pine (*Pinus ponderosa*) (Soil Survey Division, 2006). In 1994, the study area was seeded to permanent grasses, which have been maintained on the site to the present. Soils at the site have a xeric moisture regime (Soil Survey Staff, 1999). Mean annual precipitation (MAP) at the site is estimated to be ~700 mm based on soil survey information (Barker, 1981). A weather station was installed at the site to measure hourly shortwave radiation, relative humidity, air temperature, wind speed, and precipitation. Precipitation measurements were made using a tipping-bucket rain gage equipped with an antifreeze-containing snowfall adapter (CS705, Campbell Scientific, Logan, UT, USA) during 2001 and 2002. However, due to the relatively short record and some data gaps, we have used precipitation data from the nearest weather station at Moscow, Idaho, located ~16 km east of the study site for comparing relative amounts and timing of precipitation. MAP is 597 mm based on a 108-year record, and 73% of this is received between November 1 and May 31 (Western Regional Climate Center, 2003).

2.2. Seasonal perched water table monitoring

The catchment was instrumented with 135 monitoring wells installed on a 10 × 15-m grid pattern within the catchment (Fig. 1). Installation of the wells began with extraction of an intact soil core to the depth of the fragipan. Genetic horizons and their depths were recorded for each core. Wells were installed by inserting slotted PVC pipe into each hole and extending up to a depth of ~25–30 cm below the soil surface. A solid PVC pipe was then threaded onto the slotted pipe to a height of ~30 cm above the soil surface. Sand was packed in the annular space around the slotted portion of the well to ensure good hydraulic contact. Bentonite clay was packed around the top of the well to prevent preferential flow. Wet/wet pressure transducers (model # PX26-005DV, Omega Technology) were inserted into wells to a depth corresponding to the upper surface of the fragipan. The pressure transducers were connected to dataloggers (model CR10, Campbell Scientific, Logan, UT, USA). Height of the PWT above the fragipan surface was recorded at 12-h intervals during five water table seasons from 1997–2002. The pressure transducers exhibited temperature dependence when calibrated in the laboratory, so data were corrected for temperature dependence using the temperature of water inside monitoring wells as measured with copper-constantan thermocouples. PWTs were measured manually at least once per season and compared to electronic readings. Data from wells with electronic readings differing by more than 5 cm from manual readings were discarded. Block diagrams of the study area showing elevation, depth to fragipan, and PWTs were constructed using Surfer (RockWare, Inc., Golden, Colorado, USA) software.

2.3. Soil moisture measurements

Two sites were established in the west half of the study area to monitor soil moisture (Fig. 1). Soil moisture was measured using water content reflectometers (WCR) probes (model # CS615, Campbell Scientific, Logan, UT), placed horizontally at 10-cm depths from the soil surface to the lower boundary of the E horizon. The reflectometers were connected to a datalogger (model CR10, Campbell Scientific, Logan UT, USA) and daily measurements were recorded for the five-season study period from November 1998 to May 2002. Data were not collected during the period from July 29 through November 29, 1998 due to equipment problems.

2.4. Saturated hydraulic conductivity measurements

Hydraulic conductivity was measured within the catchment in situ by calculating the flow rate of water into a borehole with a Guelph constant-head permeameter (model # 2800KI, Soil Moisture Equipment Corp., Santa Barbara, CA, USA). K_{sat} measurements were made at nine locations along a transect ~1 m from each of the monitoring wells (Fig. 1). Measurements were attempted for each genetic horizon described in the well core descriptions; horizonation was verified while augering the boreholes at each location. After determining a spatial trend was not apparent, additional K_{sat} measurements were made at five locations within the catchment.

2.5. Isolated hillslope plot

A 35 m × 18 m hillslope plot was established on the west side of the catchment with an average slope of 20% and aspect of 345° (Fig. 1). The plot was isolated hydrologically from the rest of the catchment using tile lines and plastic sheeting following methodology similar to that of Parlange et al. (1989). An upper tile line was installed on top of the fragipan to divert incoming lateral subsurface flow and a lower tile line was installed to collect and divert the outgoing lateral flow to an automated tipping-bucket flow measuring device. A datalogger recorded the bucket tips every 15 min. All sides of the plot were lined with plastic sheeting, and incoming surface runoff was diverted using galvanized sheet metal borders. Outgoing surface runoff was measured using a trough draining to a similar tipping-bucket flow gauge.

Six kg of KBr were buried at a depth of ~60 cm in a 7.5-cm-diameter augered hole located 7 m upslope from the lower boundary and 7 m from the west boundary of the plot. An automatic water sampler was placed with the tipping bucket for tile flow and programmed to collect perched water samples from the tipping bucket every 2 or 4 h. Samples were refrigerated until analyzed for Br-colorimetrically on an autoanalyzer using Chloramine-T (Switala, 1990).

3. Results and discussion

All soils examined at the study site exhibit similar horizonation consistent with that described for the Santa series. A profile typically consists of an Ap–Bw (or BE)–E–Btxb horizon sequence (Table 1). Depth to the fragipan averages 71 cm, but ranges from 29 to 118 cm (Fig. 1). In general, depth to fragipan is greatest in the concave parts of the landscape and least in convex areas. Textures are silt loam in the Ap, Bw, and E horizons; fragipans have a silty clay loam texture, extremely firm moist rupture resistance, and coarse and very coarse prismatic structure. Roots in the fragipan are limited to planar voids between the peds. In addition, there is little pore continuity observed within peds, suggesting that the inter-pedal voids represent the primary pathways of vertical water movement.

3.1. Hydraulic conductivity

Data obtained using the Guelph permeameter show a trend of decreasing K_{sat} with depth in soils of the catchment (Table 2). K_{sat} of Ap and Bw/BE horizons is an order of magnitude greater than E horizons and two orders of magnitude greater than Btxb horizons. This trend has also been reported for similar soils of the region, although our K_{sat} values are lower by approximately one-third (Reuter et al., 1998; McDaniel et al., 2001). Our values are also considerably less than lateral hillslope-scale K_{sat} values for this catchment of 15.1, 2.1, and 0.6 m d^{-1} for the Ap, Bw/BE, and E horizons (Brooks et al., 2004). However, it is clear that the potential for rapid lateral redistribution of water is greatest when PWTs are in Ap horizons, and decreases with depth in the pedon. Macropores in the Ap horizon, many of which appear to be biological in nature, are likely responsible for the higher K_{sat} values.

3.2. Water content and PWTs

It has been shown that the seasonal PWT levels in these soils rise relatively rapidly in response to snowmelt and precipitation and fall during periods of freezing temperatures and no precipitation (McDaniel et al., 2001). One of the goals of this research was to establish the relationship between soil water content and PWT dynamics. To do this, volumetric water content data from WCR1 and WCR2 were compared with PWT levels in the nearest monitoring wells located <4 m away. Data obtained from both sites showed similar trends; for brevity, only data from WCR1 are presented.

Table 1
Horizon depths and thicknesses for soils within the study catchment

Horizon	Average depth (cm)	Minimum thickness	Maximum thickness
Ap	0–22	10	36
Bw/BE	20–52	10	76
E	52–71	3	46
Btxb	71+	–	–

Data represent 135 samples.

Table 2
In situ K_{sat} determined using a Guelph permeameter

Soil horizon	Mean K_{sat} (cm d^{-1})	Min. K_{sat}	Max. K_{sat}	Number of samples
Ap	31.0	8.5	286	15
Bw/BE	12.2	1.4	27.5	17
E	4.2	0.5	51.7	10
Btxb	0.9	0.01	7.1	14

Comparison of PWT hydrographs and volumetric water content at WCR1 illustrate that parts of the Ap horizon were saturated for only brief periods of time (Fig. 2a). This appeared to occur three times during 2001 and six times during 2002, with the saturation duration lasting from less than 2 days to 4 days (Fig. 2a). Although a clear relationship between apparent time of saturation and θ_v cannot be seen, data show that highest PWT levels corresponded with volumetric water contents that ranged between 50 and 55%. Additionally, θ_v only varied within a range of ~0.10 (0.45–0.55) during the entire period of episaturation.

Comparison of the PWT hydrographs and water content in the BE horizon indicates that when episaturation occurred at the level of the WCR probe located in the BE horizon, volumetric water content was ~46–47% (Fig. 2b). Furthermore, as the PWT rose above and fell below this level, water content was maintained within a fairly limited range. In 2000, the PWT level did not reach the level of the lower WCR probe until the first part of March, and this corresponded to a volumetric water content of ~46%. For the next 3–4 months, water content only varied between ~43–47% as the PWT level rose above and fell below the level of the WCR probe. A similar pattern was observed during the 2001–2002 season. The PWT formed in early January and corresponded to a water content of ~46% as measured by the WCR probe. Volumetric water content then varied within a 4–5% range until PWT dry down occurred in late April–early May.

It is apparent from these data that only a relatively small (~5%) increase or decrease in volumetric water content accompanies the change from saturated to unsaturated conditions, and thus the rise and fall of PWTs. It is also clear that these soils never achieve 'field capacity' during the PWT season. Rather, water contents decrease to slightly below that required for saturation because of the close proximity to the PWT. It is for this reason that relatively small additions of water through precipitation or snowmelt result in the rapid re-establishment of PWT levels. Assuming an average soil porosity of 0.50 and an increase in volumetric water content of 5% needed to achieve saturation, as little as 0.5 cm of precipitation will result in a 10-cm rise in PWT levels across the catchment.

3.3. PWTs vs. catchment outflow

Because monitoring well data have shown that episaturation occurs at or near the soil surface on several occasions during most years (McDaniel et al., 2001), we wanted to examine the relationship between PWTs and the generation of runoff. The main hydrological feature of the study area is an ephemeral drainageway that bisects the catchment (Fig. 1). The flume

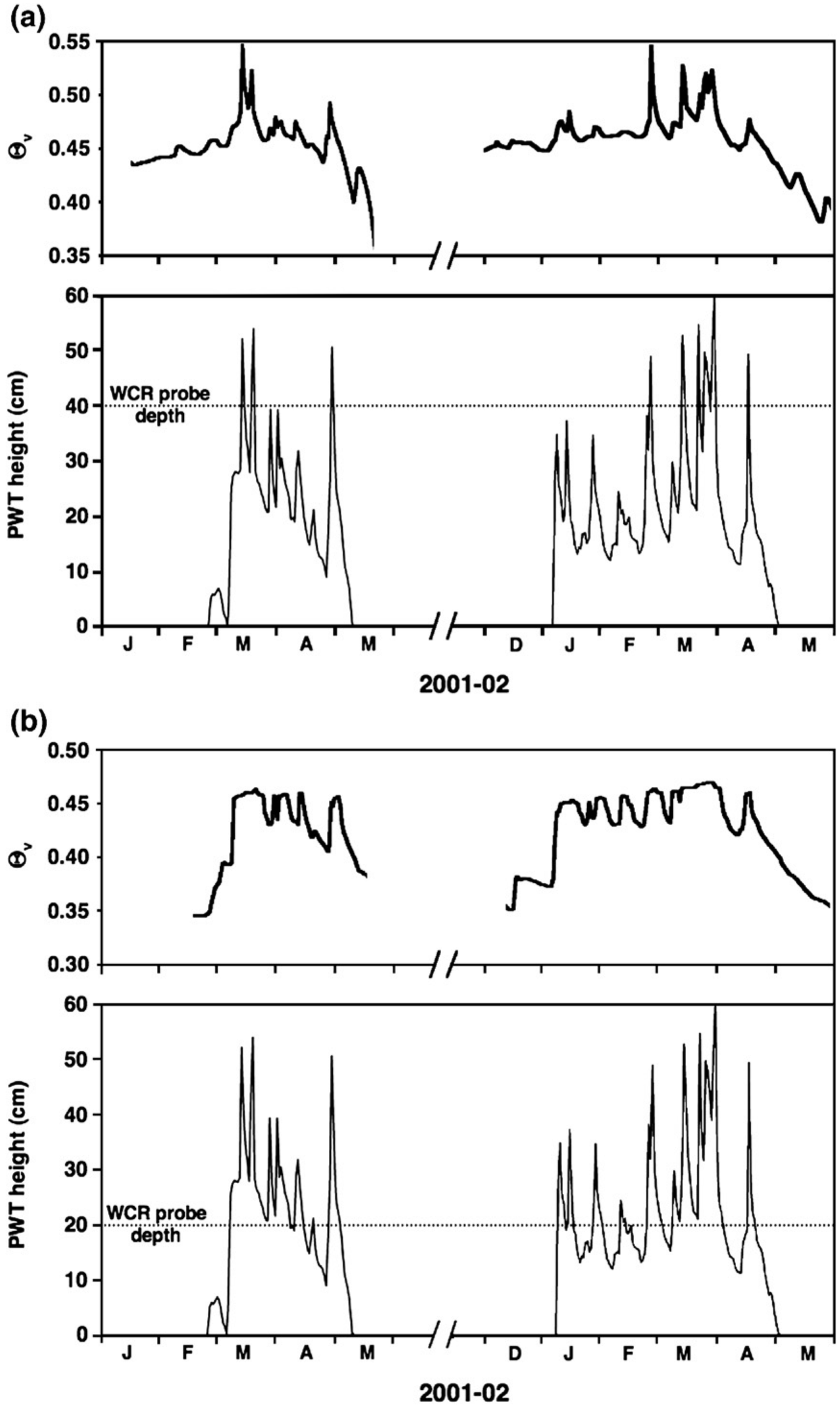

Fig. 2. Relationship between perched water table height and volumetric water content in (a) the Ap horizon and (b) the BE horizon of a Fragixeralf (Fragic Luvisol).

installed at the base of the drainage recorded surface water flow in this drainage from 1–4 months during the course of this study (Fig. 3). Timing as well as duration of flow varied considerably from year to year, as water-year precipitation ranged from 77% of average in 2000–01 to 148% of average in 1998–99 (Table 3). Examination of the flume data suggests the existence of two types of runoff events. In all cases, peak outflow was immediately preceded by relatively large quantities of rainfall or snowmelt. The sharp outflow spikes reflect relatively rapid response to direct precipitation or snowmelt on saturated soil, and the generation of overland stormflow. We believe the shoulders of the sharp spikes are a result of return flow, which is generated as subsurface stormflow emerges from the soil as it encounters areas of decreased slope gradients and convergent flow (Dunne et al., 1975). Gburek et al. (2006) reported similar surface runoff responses in a Pennsylvania watershed containing fragipan soils.

The network of monitoring wells provides a means for spatially explicit depiction of PWTs across the landscape. For each well, PWT height and total soil profile thickness above the fragipan were used to calculate the percentage of the soil profile

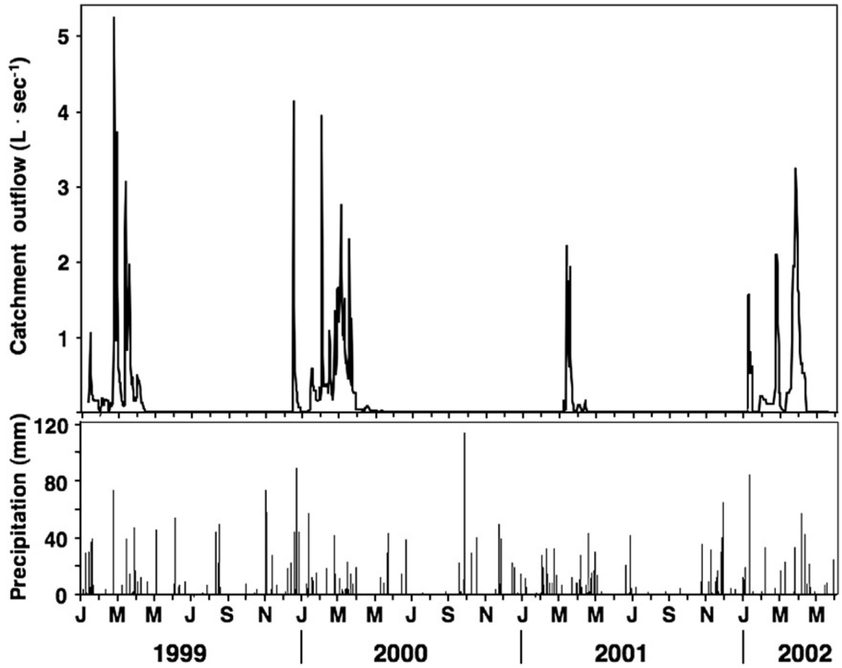

Fig. 3. Surface outflow measured in flume located at the mouth of the catchment drainageway and daily precipitation measured at Moscow, ID, 16 km east of the study site.

that was saturated; profiles were considered completely saturated when PWT height was within 5% of the profile thickness. These data are shown for the dates when peak outflow was measured in the flume (Table 4). Averaging across the catchment, it appears that peak surface outflow is generated when PWT height is ~50 cm or more and at least ~25% of the catchment profiles are saturated to the surface.

The rapid change in soil profile saturation can be illustrated spatially for the 24-h period that encompasses the peak outflow generated in March 2001 (Fig. 4). From 12:00 to 18:00, average PWT height within the catchment increased from 47 cm to 65 cm as a result of warming temperatures and rapid snowmelt. The number of profiles that were saturated to the surface increased from 22 to 49 during this period. By 12:00 of the following day, only 28 profiles were saturated and peak outflow had passed. The patterns shown in Fig. 4 indicate that saturation-excess runoff is being generated at several locations within the catchment. These include hillslope positions on both the east and west sides of the drainageway where, in general, depth to fragipan tends to be less than the catchment average (see Fig. 1). Similar patterns were seen for other peak outflow events as well. It appears that in response to high precipitation and/or snowmelt events, PWTs quickly rise to the surface where fragipans are relatively close to the surface. These areas subsequently generate saturation-excess runoff.

Table 3
Water year (Nov–May) precipitation recorded at Moscow, ID

	Water year				
	1998–99	1999–2000	2000–01	2001–02	2002–03
Total precipitation (mm)	632	554	337	473	620
% of average	144	128	77	108	141

Average is based on 108 years.

It is interesting that such expression of VSA hydrology occurs within a catchment dominated by a single soil series. We suggest that the implications of VSA hydrology in this and similar catchments may ultimately be tied to geomorphic evolution. Specifically, the variable depths to the fragipan give rise to VSA hydrology, which in turn influences the spatial pattern of runoff generation under native conditions. However, modification of the study catchment land surface by decades of tillage and farming practices makes this difficult to evaluate. At the very least, it is clear that export of sediment and solutes from the catchment via runoff is not uniform across the component hillslopes, despite the fact that all soils in the catchment contain fragipans.

3.4. PWTs, solute transport

The isolated hillslope plot was utilized to measure surface and subsurface flow and subsurface transport of applied Br^-. Detectable levels of Br-first appeared in subsurface throughflow samples taken 9 h after application (Fig. 5), indicating a mean pore velocity of 18.7 m d^{-1}. Assuming an average porosity of 0.50, this is equivalent to a K_{sat} of ~9 m d^{-1}. PWT levels in

Table 4
Peak outflow events with associated perched water table (PWT) heights and soil profile saturation

Peak outflow event	Average PWT height (range) (cm)	Number of profiles saturated	% of profiles saturated
2/25/99	57.4 (21–102)	33	26
12/18/99	58.8 (23–104)	57	45
3/13/01	64.5 (33–109)	49	42
3/28/02	50.1 (7–113)	35	30

The number and percentage of saturated profiles are based on properly functioning wells on the respective dates.

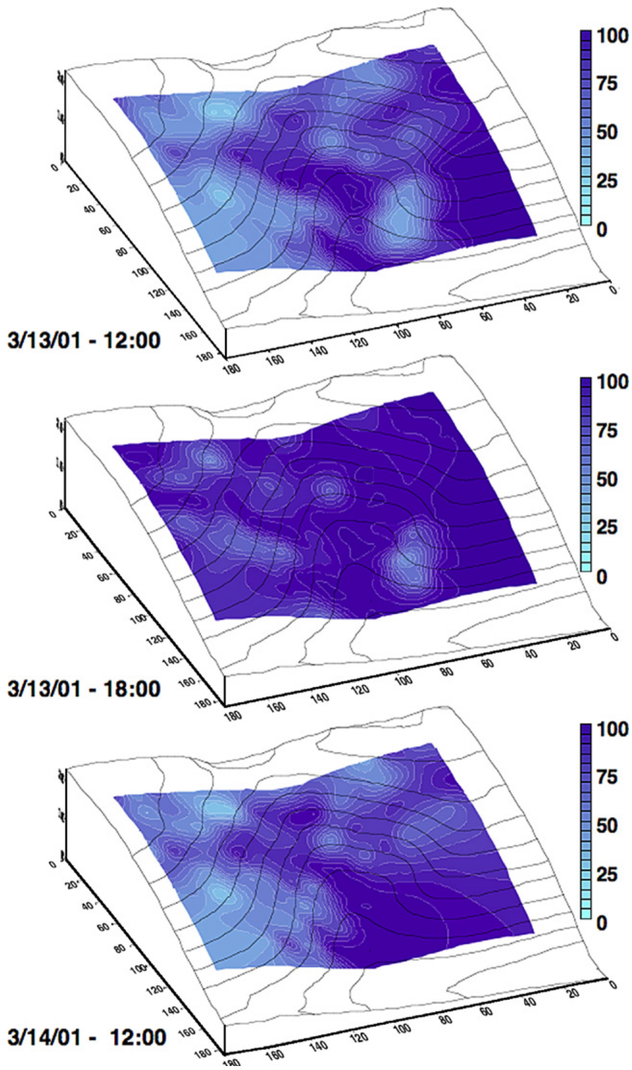

Fig. 4. Spatial distribution of soil profile saturation. Shading indicates the percentage of the soil profile above the fragipan that is saturated. Sequence represents a 24-h period coinciding with peak runoff generation.

monitoring wells located within the plot were maintained in Ap horizons at an average depth of ~15 cm below the soil surface during this period between tracer application and initial detection (data not shown). This suggests that such high rates of movement occur when PWT heights are in Ap horizons with greater K_{sat} and where preferential flow through macropores is more likely. These high preferential flow velocities likely approach those observed with overland flow and thus may have significant impacts on local surface water quality (Seiler et al., 2002). A second concentration maximum was observed 58 h after Br^- application, representing a mean pore velocity of 2.9 m d^{-1}. PWT levels had dropped to ~30 cm below the soil surface. This rate is attributable to piston flow and represents a K_{sat} of ~1–2 m d^{-1}. Comparable values have been obtained for similar study sites in the region (Reuter et al., 1998). These data illustrate the importance of PWT height and depth to fragipan in determining solute transport rates in these landscapes.

3.5. PWTs and subsurface flow

No surface flow was measured exiting the isolated surface plot during the course of monitoring. However, subsurface flow accounted for the majority of water loss measured from the plot during the months when evapotranspiration was minimal. Moreover, 89% of the precipitation received on site left the plot as subsurface lateral flow during the 3-month period from 16 Feb to 17 May 2000 (Brooks et al., 2000). This is similar to that reported in Ohio, where subsurface lateral flow above a fragipan was estimated to account for >80% of the February precipitation (Miller et al., 1971). Although continued monitoring of this plot was not possible because of technical problems, the available data suggest that subsurface lateral flow is a large component of the overall catchment water balance.

Upon reaching the lower-gradient footslope positions occupying the lower elevations of the catchment, subsurface lateral flow can become surface runoff (Seiler et al., 2002). Such areas of return flow were observed in the catchment as localized seeps. Based on flume data and evapotranspiration modeling for 2000–03, 57% of the precipitation received on an annual basis is lost from the catchment via evapotranspiration, 40% leaves as surface runoff via the flume, 2% leaves as deep percolation, and 1% left as lateral flow (Brooks et al., 2007). The surface flow measured in the flume includes return flow, where subsurface flow generated on upper

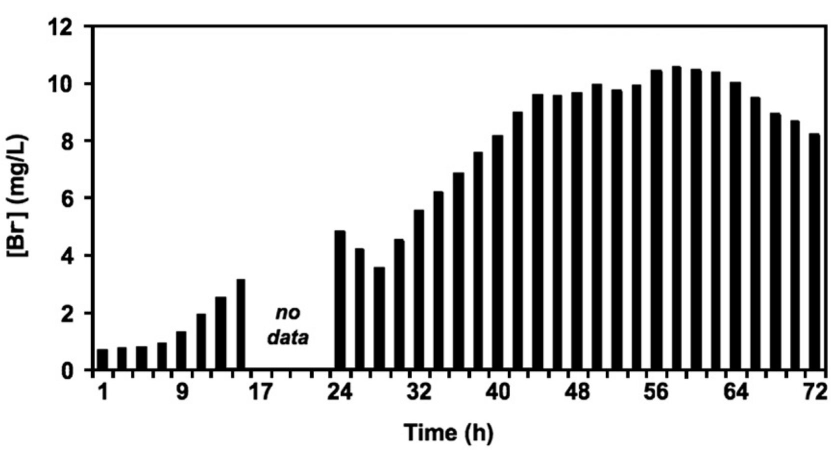

Fig. 5. Hourly Br concentration in perched water flowing out of isolated hillslope plot. Because of battery failure, no data were obtained between 17 and 23 h.

hillslopes becomes surface runoff upon encountering lower-gradient slopes at the base of the hillslopes. The lateral flow component of the catchment water loss is small because of the low-gradient slopes at the lower catchment boundary. Most of the subsurface lateral flow becomes return flow before it leaves the catchment.

4. Summary

It has long been recognized that fragipans have an important effect on near-surface hydrological process. Results from this study demonstrate that these fragipans, through their role in the formation of PWTs, cause significant redistribution of annual precipitation in sloping landscapes. However, the processes responsible for redistribution of precipitation are not uniformly expressed across the catchment, despite the fact that all soils have fragipans and relatively similar morphology. PWTs rise rapidly in response to precipitation and snowmelt events during the winter months. Areas of the catchment where fragipans are relatively close to the surface tend to become saturated more quickly and generate saturation-excess runoff. Overall, ~41% of the annual precipitation leaves the catchment as surface outflow, which includes both surface runoff and return flow.

The combination of low drainable porosity, relatively shallow depth to the fragipan, and relatively high lateral saturated conductivity results in a very flashy hydrologic system in which the percentage of the catchment that produces runoff varies considerably, both spatially and temporally, during periods of precipitation and snowmelt. Subsurface lateral flow on top of the fragipan accounts for redistribution of up to 90% of the precipitation received on site during late winter/early spring. Moreover, this lateral flow may be very rapid, with mean pore velocities approaching 19 m d^{-1}.

Acknowledgments

This work was made possible through funding from the US Geological Survey (1434-HQ-96-GR-02667) and the University of Idaho Research Office.

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